The ρ-mass, width and line shape in $\bar{p}p$-annihilation at rest into $\pi^+\pi^-\pi^0$

Crystal Barrel Collaboration

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A high-statistics data sample on $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$ is studied to deduce the mass, width, and line shape of charged and neutral ρ mesons. We find that the line shape is well described by a relativistic Breit-Wigner function. We find mass degeneracy of the $\rho^\pm$ and ρ^0 masses when mixing with the ω in its $\pi^+\pi^-$ decay mode is taken into account. A fit with one mass and width for the three ρ charge states yields $m_\rho = (763.0 \pm 1.3)$ MeV and $\Gamma_\rho = (149.5 \pm 1.3)$ MeV. The mass difference between charged and neutral ρ's is determined to $(1.6 \pm 0.6 \pm 1.7)$ MeV. A possible influence on the ρ mass due to the isobar approximation is discussed.

The 3 charge states of ρ mesons are, of course, fully established; they pose no difficulty in assigning them to the ground-state nonet of vector mesons. But their actual parameters are not too well determined. The Particle Data Group quotes different mean values for the mass of charged and neutral ρ mesons while experiments investigating a possible mass difference find consistent masses for $\rho^\pm$ and ρ^0 [3].

Ideally, ρ mesons should be studied in their decay to two pions with no third particle present in the same kinematic region to avoid the possibility of rescattering or of three-body interactions. Ideally suited for a discussion of the exact mass and width of the ρ^0 and of the ρ^0 line shape is therefore e^+e^- annihilation into $\pi^+\pi^-$ [1]. The interference between ρ and the two-pion decay of the ω is also best studied in this process [4]. On the other hand, processes in which all three charge states of the ρ are produced with equal abundancy may

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be best suited to search for a mass difference between charged and neutral ρ's. Antiproton-proton annihilation at rest into $\pi^+\pi^-\pi^0$ is known to be dominated by ample production of ρ mesons with about equal rates in all 3 charge states [2]. A study of this reaction thus allows to search for a mass difference between ρ^0 and $\rho^\pm$ mesons and to investigate if three-body effects lead to significant changes in the precise mass value. In this letter we report on a study of the ρ resonance produced in the reaction

$$\bar{p}p \rightarrow \pi^+\pi^-\pi^0 \,. \tag{1}$$

The study is based on nearly 200 000 ρ mesons in each charge state.

The data for reaction (1) were collected with the Crystal Barrel detector at LEAR. It has been described in detail elsewhere [5]; here we give only a short summary. A beam of 200 MeV/c antiprotons is extracted from LEAR. The $\bar{p}$'s are stopped in a liquid H_2 target at the center of the detector. The target is surrounded by a silicon vertex detector [6] and a cylindrical drift-chamber (JDC) with 23 layers. The JDC is surrounded by a barrel-shaped calorimeter consisting of 1380 CsI(Tl) crystals in a pointing geometry. Data and data selection for reaction (1) were already described in [7] where the branching ratio for reaction (1) was also determined to be $(5.82 \pm 0.43) \cdot 10^{-2}$ per annihilation. Reaction (1) is identified by a kinematic fit with 5 constraints (energy and momentum conservation and the mass of the π^0 are imposed) to the $\pi^+\pi^-\pi^0$ hypothesis. Background is at a negligible level.

In order to demonstrate our mass calibration and resolution we also identified reactions $\bar{p}p \rightarrow \pi^+\pi^-\pi^0\pi^0$ and $\bar{p}p \rightarrow \pi^+\pi^-\pi^0\eta$. The $\pi^+\pi^-\pi^0$ invariant mass distributions show clear peaks due to the reaction $\bar{p}p \rightarrow \pi^0\omega$ and $\eta\omega$, respectively, above a small background. A fit to the distributions gives a mass resolution of $\sigma_{mass} = 8$ MeV and a ω mass of 780.75 MeV. The mass differs from the nominal ω mass by 1.2 MeV. The difference could be due to a wrong magnetic field calibration and could effect the mass of the ρ^0 and of the $\rho^\pm$ differently. We take the mass difference between our measured ω mass and the accepted value as an estimate of our systematic error and correct masses in this mass range by $(+1.2 \pm 1.2)$ MeV.

In Fig. 1 we present the Dalitz plot of reaction (1), in Fig. 2 the three ρ decay angular distributions. The Dalitz plot with 725 000 events is dominated by production of ρ mesons in all 3 charge states; the partial wave analysis assigns 81% to the 3 ρ's. The decay angular distributions show a $\sin^2\Theta$ behaviour – as expected for annihilation from the $^3S_1$ initial state – above a small constant distribution which reflects contributions from $^1S_0$ and P-state annihilation. The 2 peaks in the decay angular distribution of one ρ originate from the reflection of the other 2 ρ charge states. These are sometimes called Bouchiat horns [8]. The slightly higher intensities of the ρ^+ and ρ^- reflections in the

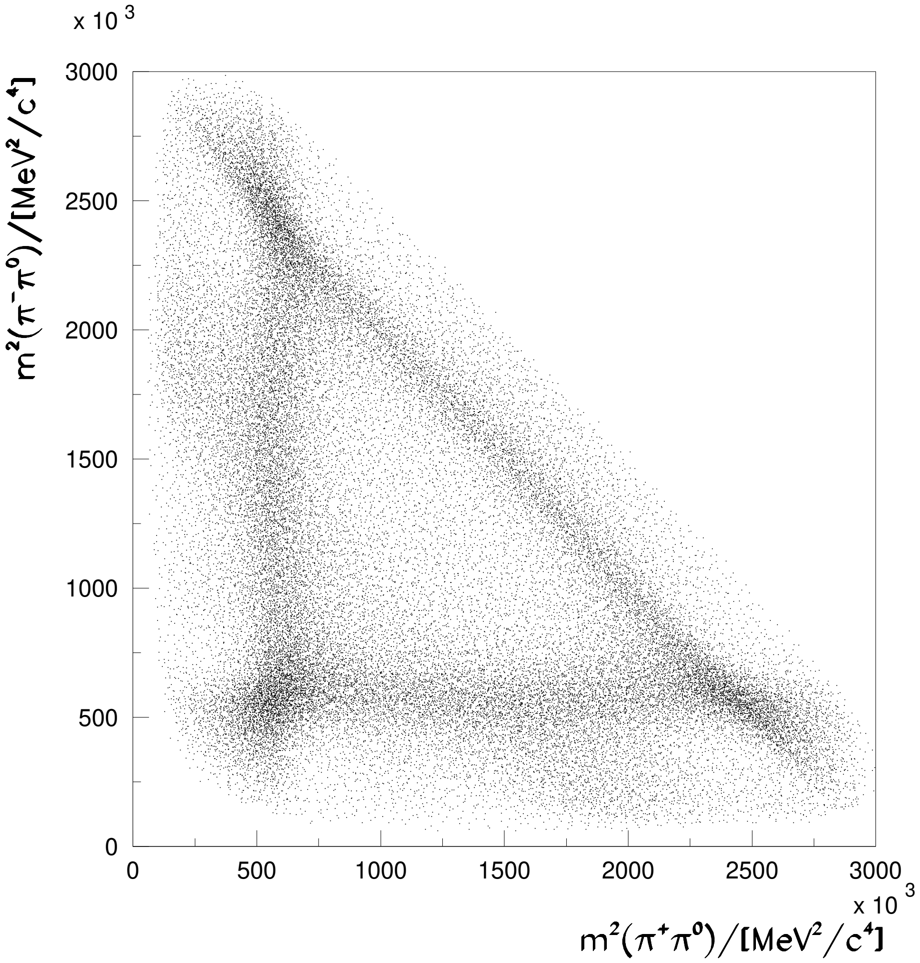

Fig. 1. $\pi^+\pi^-\pi^0$ Dalitz-plot for antiprotons stopping in a liquid H_2 target.

decay angular distribution are due to a small contribution from isovector initial states, likely from the ${}^1S_0$ initial state. Careful inspection of the intensity at small $\pi^+\pi^-$ invariant masses which is larger on the diagonal of the Dalitz plot suggests interference contributions from higher mass ρ^+ states even though the effect is hardly visible. We also expect the ρ^0 line shape to be distorted by $\rho-\omega$-interference since the ω has a small decay probability into $\pi^+\pi^-$. The $f_2(1270)$ is evident in the data. A further tensor state, the $f_2(1565)$ is hidden in the ρ^+-ρ^- interference region in the lower left corner of the Dalitz plot.

Fits to Dalitz plots with more than 700 000 events require binning of the data. For technical reasons, this binning is too coarse to allow a study of $\rho-\omega$-interference directly on the Dalitz plot. Therefore we present here only a discussion of the ρ line shapes and refer the reader to [9] where full account will be given of the analysis of the $\pi^+\pi^-\pi^0$, $\pi^-\pi^0\pi^0$ and $\pi^-\pi^-\pi^+$ Dalitz plots. From that analysis we use here only the branching ratio

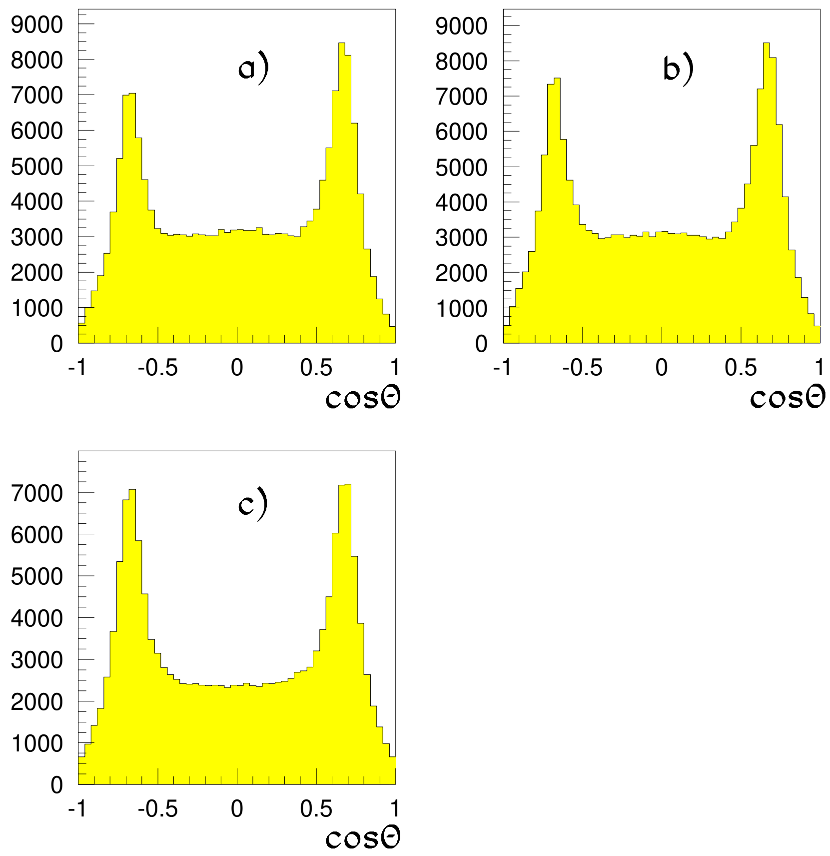

Fig. 2. Decay angular distributions of the three ρ charge states. The ρ's are defined by a $\mathrm{m}_\rho \pm \frac{1}{2}\Gamma_\rho$ mass cut. a) ρ^+; b) ρ^-; c) ρ^0 decay angular distribution.

$$BR(\bar{p}p \to \rho^0\pi^0) = (1.58 \pm 0.12)\% \,. \tag{2}$$

The ρ line shapes are distorted in the 3 corners of the Dalitz plot by ρ-ρ interference. Therefore we restrict the line shape analysis to an angular range to which ρ-ρ interference does not contribute. The 3 mass distributions in Fig. (3a,b,c) are thus generated with a cut in the ρ decay angular distributions $-0.5 < \cos\Theta < 0.5$ (see Fig. 2). The angular distributions also show that the ρ line shapes are hardly effected by interference with the $f_2(1270)$.

We use a relativistic Breit-Wigner amplitude of the form

$$\mathrm{BW}_\rho = A_\rho \cdot \frac{D_1(p) \cdot m_\rho \cdot \Gamma_\rho \cdot B_1^\rho(q, q_\rho)/\rho(m_\rho^2)}{m_\rho^2 - s - i \cdot m_\rho \cdot \Gamma_\rho \cdot B_1^\rho(q, q\rho)^2 \cdot \rho(s)/\rho(m_\rho^2)}$$

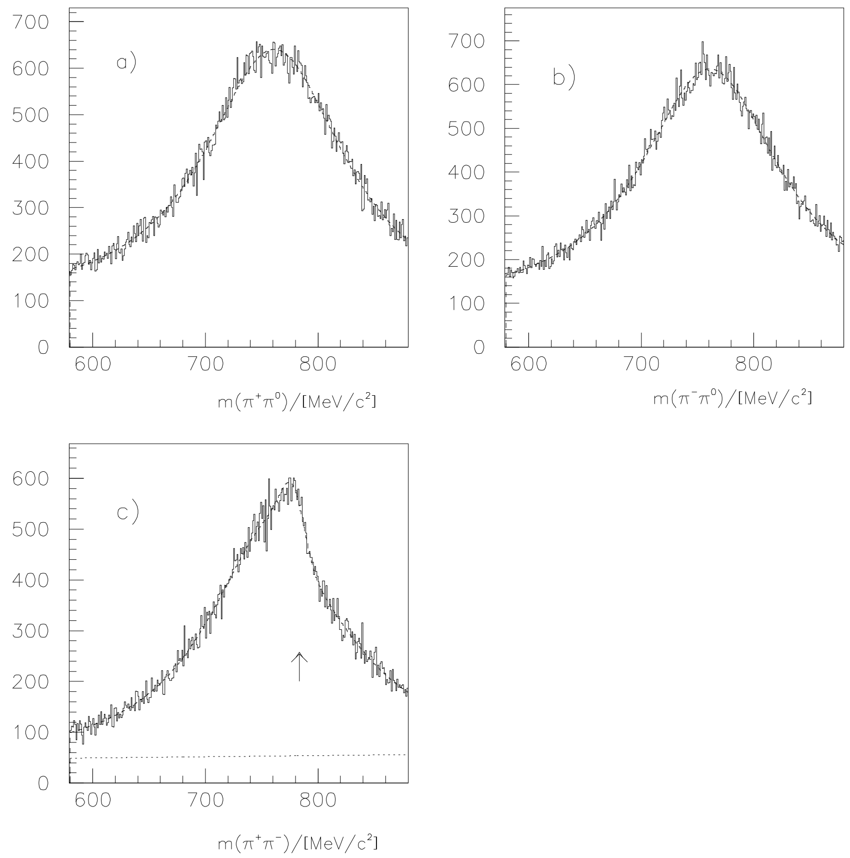

Fig. 3. $\pi\pi$ invariant mass distributions for $\bar{p}p \to \pi^+\pi^-\pi^0$ in $\bar{p}p$ annihilation at rest. A cut has been applied to exclude the 3 ρ-ρ interference regions. The solid line represents fits with relativistic Breit-Wigner amplitudes. a) $\pi^+\pi^0$ mass; b) $\pi^-\pi^0$ mass; c) $\pi^+\pi^-$ mass. For c) $\rho - \omega$-interference was introduced. The arrows in (c) indicate the mass of the ω meson. The dotted line shows the non-ρ contribution.

with a production amplitude A_ρ. B_1^ρ is the Blatt-Weisskopf factor with ℓ=1:

$$B_1^\rho(q, q_\rho) = \frac{D_1(q)}{D_1(q_\rho)}$$

$$D_1(q) = \frac{q}{p_r}\sqrt{\frac{2}{(\frac{q}{p_r})^2 + 1}}$$

p is the decay momentum of $\bar{p}p$ system into pion and the dipion, q the decay momentum of the dipion in its rest frame and p_r is set to 200 MeV/c (no significant changes are observed for modest variations of this quantity). The

2-body phase space is given by the variable $\rho(s)$ where s represents the squared dipion mass.

With this formula we fit the $\pi^+\pi^0$ and $\pi^-\pi^0$ mass distributions. The two charged ρ-mesons have masses which are fully compatible with each other (with a mass difference of 0.4 MeV). The neutral dipion mass distribution shows an anomaly in the region of the ω mass which is due to ρ-ω interference. The ω has a small decay rate into $\pi^+\pi^-$, hence the two reactions $\bar{p}p\to\pi^0\rho$ and $\pi^0\omega$ can interfere. This effect leads to a bad χ^2 for a fit of the neutral dipion mass distribution. Hence we introduce a second amplitude BW_ω for $\bar{p}p\to\pi^0\omega$, $\omega\to\pi^+\pi^-$ and fit the $\pi^+\pi^-$ mass distribution with a function including ρ-ω interference [7]. With this extended amplitude the fit gives a much improved χ^2. The mass resolution is taken into account by a folding procedure. The phase between the ρ and ω production amplitude is $(5.9 \pm 0.6 \pm 2.0)^\circ$. The result of the fit is superimposed in Fig. 3 as solid line. Mass and width of the ρ^0 are now given by

$$m_{\rho^0} = (762.3 \pm 0.5 \pm 1.2)\ \mathrm{MeV} \quad \Gamma_{\rho^0} = (147.0 \pm 2.5)\ \mathrm{MeV}$$

We now comment on our results on mass and width of the three ρ mesons. We find line shapes for charged ρ's fully compatible with relativistic Breit-Wigner amplitudes when barrier penetration factors in production and decay and mass dependent widths are taken into account. The ρ^0 line shape is significantly distorted by $\rho-\omega$-interference; the ρ^0 mass is however not influenced by this effect and is fully compatible with the masses of ρ^+ and ρ^-. Imposing equality of the ρ^+ and ρ^- masses and widths in the fit we obtain

$$m_\rho = (763.0 \pm 0.3 \pm 1.2)\ \mathrm{MeV} \tag{3}$$

$$\Gamma_\rho = (149.5 \pm 1.3)\ \mathrm{MeV} \tag{4}$$

$$m_{\rho^0} - m_{\rho^\pm} = (1.6 \pm 0.6 \pm 1.7)\ \mathrm{MeV} \tag{5}$$

Compatible masses and widths were also found at LEP with a similar precision [11]: $M_{\rho^\pm} - M_{\rho^0} = (0.0 \pm 1.0)$ MeV/c^2 and $\Gamma_{\rho^\pm(770)} - \Gamma_{\rho^0(770)} = (0.1 \pm 1.9)$ MeV/c^2.

The masses of charged and neutral ρ-mesons are significantly smaller than those listed by the Particle Data Group [3]. We conjecture that the reason for the lower mass could be due to rescattering of the ρ daughter pions off the 'spectator' pion. The effect of rescattering in $\bar{p}p\to K_sK_L\pi^0$ has been analysed using dispersion relations [12]. The technique requires integration over $K(\bar{K})$ and $K\pi$ intermediate states up to a maximum value, a somewhat arbitrary cut-off parameter. It was found that for a reasonable choice of the cut-off the anomalously high $\Phi\pi$ production in $\bar{p}p$ annihilation can be explained. Also other dynamical consequences are predicted but these effects lead to marginal changes in the Dalitz plot. When this formalism is adapted to $\bar{p}p \rightarrow K_s K_L \pi^0$ $\rho^+\pi^- + \rho^0\pi^0 + \rho^-\pi^+$ the same cut-off parameter which reproduced the large $\Phi\pi$ branching ratio predicts a ρ mass shift of -5 MeV. The low ρ-mass found here may therefore reflect the point at which the isobar model starts to limit the precision of results.

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